A PRELIMINARY EXAMINATION OF THE EFFECT OF STRUCTURE ON THE COMPRESSIVE STRENGTH OF ICE SAMPLES FROM MULTI-YEAR PRESSURE RIDGES

J.A. Richter and G.F.N. Cox
U.S. Army Cold Regions Research
and Engineering Laboratory
Hanover, N.H. 03755

ABSTRACT

A series of 222 uniaxial constant-strain-rate compression tests were performed on vertical multi-year pressure ridge sea ice samples. A preliminary analysis of the effect of structure on the compressive strength of the ice was performed on 78 of these tests. Test parameters included a temperature of -5°C (23°F) and strain rates of 10^{-5} and 10^{-3} s^{-1}. Columnar ice loaded parallel to the elongated crystal axes and perpendicular to the crystal c-axis was consistently the strongest type of ice. The strength of the columnar samples decreased significantly as the orientation of the elongated crystals approached the plane of maximum shear. Samples containing granular ice or a mixture of granular and columnar ice resulted in intermediate and low strength values. No clear relationship could be established between structure and strength for these ice types. However, in general, their strength decreased with an increase in porosity.

INTRODUCTION

Multi-year ridge sea ice is highly variable in its structural composition. Samples taken from a multi-year ridge for mechanical testing exhibit structural ice types that reflect the history of formation of the ridge. Ice structure types include columnar ice, granular ice and a mixture of columnar and granular ice. Columnar ice may be derived from the parent ice sheets involved in the ridge building or from new congelation growth. Granulation of the ice during ridge formation may produce a fine granular material. Mixtures of granular and columnar ice can be created during the formation and consolidation of the ridge. The amounts of these ice types vary both between and within individual samples.

Studies by Peyton (1) and Wang (2) have shown large variations in the strength of first-year sea ice that depend on the ice type, grain size and crystal orientation. A review and discussion of the effects of ice structure on the strength of first-year sea ice can be found in Schwarz and Weeks (3). In a recent study on the mechanical properties of multi-year ridge sea ice, a series of uniaxial constant strain rate compression tests was performed on vertical ice samples from ten multi-year pressure ridges (4, 5). The data for the maximum stress value, or strength, of these samples had a large amount of scatter. Much of this scatter may be the result of variations in ice structure between samples. This paper presents the results of a preliminary analysis to determine the relationship between ice strength and structure in multi-year ridge samples.

SAMPLE ANALYSIS

To evaluate the structural composition of each sample a series of thin sections was prepared according to the techniques described in Weeks and Gow (6). Sections of both the tested samples and the end pieces adjacent to the test specimen were prepared. End pieces were studied to help determine inherent structural characteristics of the specimen. Horizontal thin sections were prepared from the top, middle and bottom of the test samples that were not destroyed during the test. The remainder of the sample was sectioned vertically in two cuts, one normal to the other. The ice type, grain size, and crystal orientation were determined by studying the photographs of the horizontal and vertical thin sections taken in crossed-polarized light.

In addition to thin-sectioning, backlighting was used for nondestructively determining the gross structural features of the ice. A high-intensity light was placed behind the sample before testing, and photographs were taken. After testing, the sample was again placed in front of the light and photographed at the same positions. The two sets of photographs were compared to distinguish between original and test-created ice fabrics.

SAMPLE CHARACTERIZATION

Each sample was classified according to ice type. Existing ice classification methods, such as those of by Michel (7) and Cherepanov (8), were not appropriate for multi-year ridge ice since they did not consider deformed ice types. Both of these classification schemes also required some knowledge of the ice origin; because the ridge ice was deformed, its origin was difficult to establish. Therefore, a simple ice structure

Table 1. Structural classification scheme for multi-year pressure ridge ice samples.

Ice Type	Code	Structural Characteristics
Granular	I	Isotropic, equiaxed crystals
Columnar	II	Elongated, columnar grains
	IIA	Columnar sea ice with c-axes normal to growth direction; axes may not be aligned
	IIB	Columnar sea ice having random c-axis orientation (transition ice)
	IIC	Columnar freshwater ice; may be either anisotropic or isotropic
Mixed	III	Combination of Types I and III
	IIIA	Largely Type II with granular veins
	IIIB	Largely Type I with inclusions of Type I or II ice (brecciated ice)

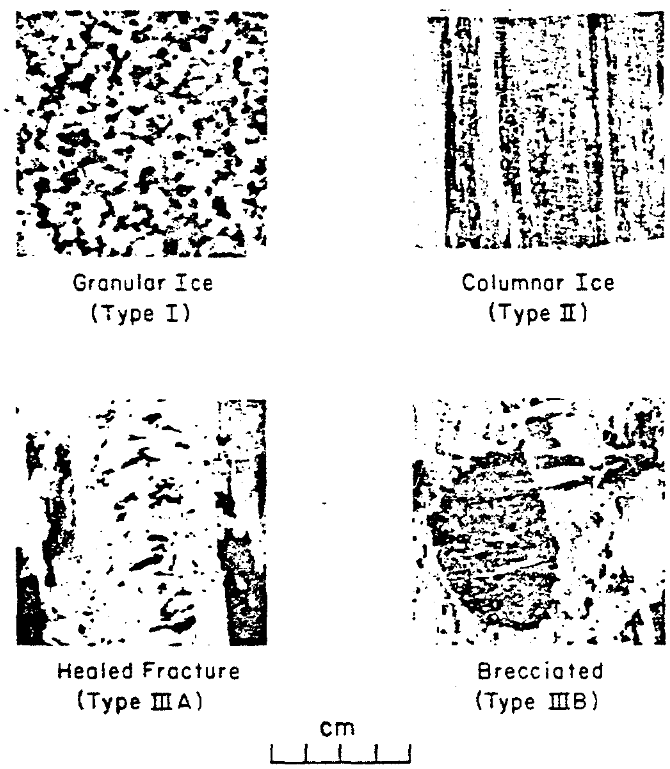


Figure 1. Structural characteristics of multi-year ice types.

classification scheme was devised for multi-year ridge sea ice. The scheme was based solely on ice structure types observed in continuous multi-year pressure ridge cores and test specimens. A summary of the classification is presented in Table 1. Figure 1 is a series of thin sections, photographed in cross-polarized light, which illustrate the principal structural characteristics of the ice types.

The structural classification scheme does not consider any genetic criteria, but the origin of each ice type may be postulated. Granular ice may be derived from snow or slush ice, from frazil, from the granulation of the sheet ice during the ridge building process, or from freezing in the void spaces in the ridge during consolidation. Columnar ice is probably largely derived from the parent sheet ice that was deformed to form the ridge. It may also form at the base of the ridge by congelation growth after ridging. The mixed ice probably originates during ridge building and consolidation. Mixtures of granular and columnar ice may form in the ridge voids (Type III). Type IIIA ice includes healed fractures, and Type IIIB ice is probably the cataclastic product of ice blocks from the parent sheet that were grounded together.

RESULTS

In the study performed on vertical multi-year pressure ridge samples (4, 5), 222 uniaxial constant-strain-rate compression tests were completed on multi-year ridge samples. A structural analysis was conducted on the first 78 compression tests to evaluate the structure-to-strength relationship. All of these tests were done at a temperature of −5°C (23°F). Of these 78 tests, 39 were conducted at a constant strain rate of 10^{-5} s^{-1} and 39 tests were conducted at 10^{-3} s^{-1}.

For each strain rate the five strongest, the five weakest, and five intermediate strength samples were chosen for detailed structural analysis. The ice was separated into these groups to make any structural variations evident.

The strength, structure, grain size and porosity of the selected samples are given in Table 2. In this table the elongation direction for the columnar ice samples refers to the angle between the columns, or elongated axes, and the loading direction (vertical). Porosity values were determined using the relationship established by Cox and Weeks (9), which relates sample salinity, density and temperature to sample porosity.

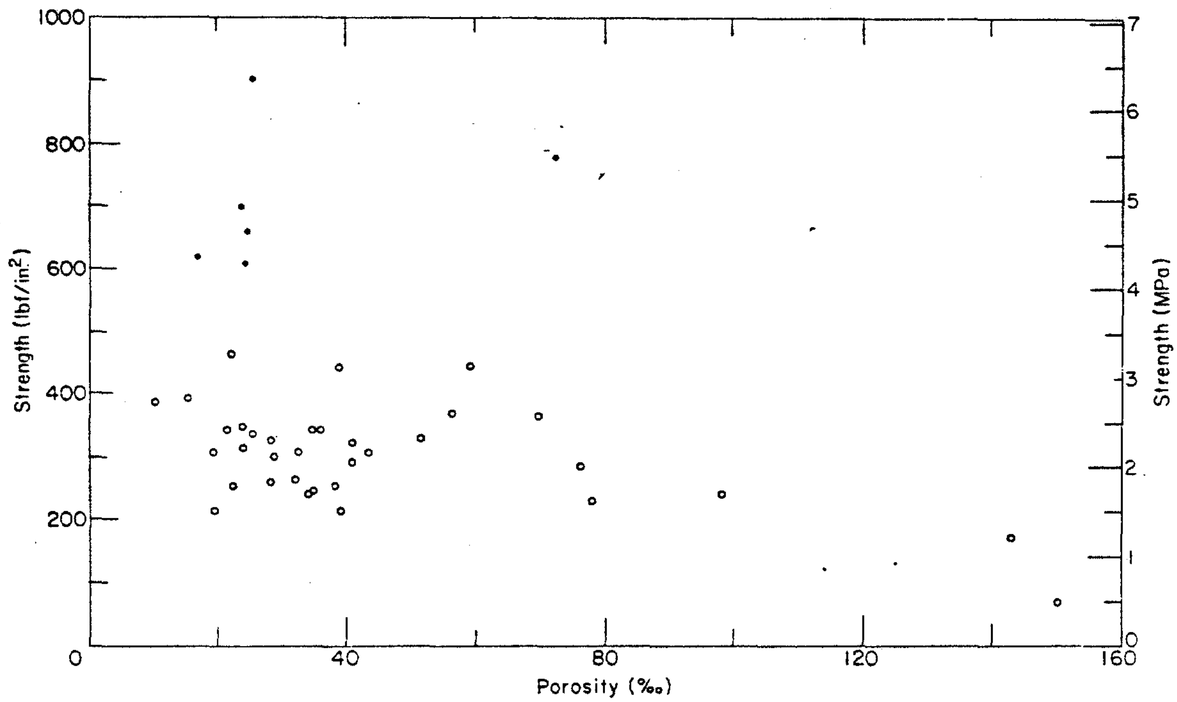
In both the 10^{-3} s^{-1} and the 10^{-5} s^{-1} tests, columnar specimens oriented with their elongated crystal axes parallel (0°-20°) to the loading direction were consistently the strongest type of ice (Type IIA). In this case the c-axes was normal to the load direction. Of these samples, specimens with aligned c-axes were stronger than those having random, planar c-axis orientations. Columnar samples having elongated crystals oriented parallel to the plane of maximum shear (30°-60° to the loading direction) gave low strength values. Randomly oriented columnar ice (Type IIB) had an intermediate strength.

Samples containing granular ice (Type I) or a mixture of granular and columnar ice (Type III) consistently resulted in intermediate and low strength values. Based on structure alone, no clear relationships could be established between structure and strength for these types of ice. However, in general, the weakest samples had much higher porosities than the intermediate strength specimens.

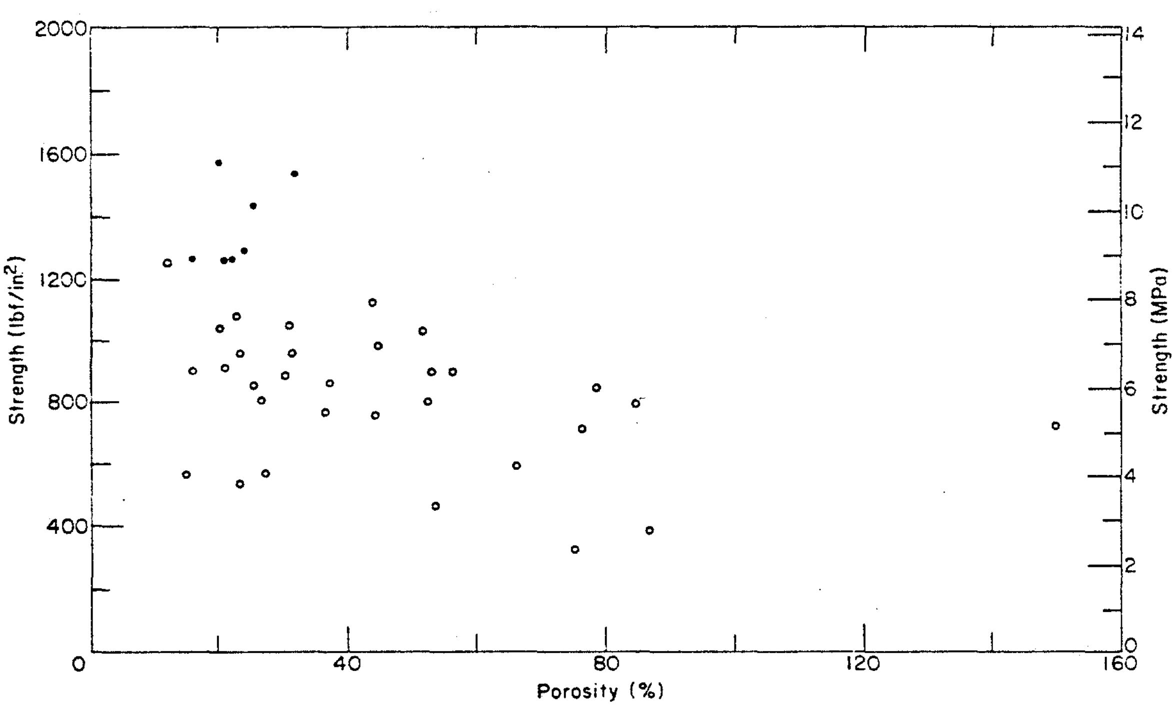
These results are best summarized in a plot of strength versus porosity. The tests performed at constant strain rates of 10^{-5} and 10^{-3} s^{-1} are presented in Figure 2. In both test cases the columnar samples with a crystal elongation of 0° with the vertical had significantly higher strength values than the other samples and had low porosity values. The remaining test samples indicate a decrease in strength with an increase in porosity. This trend is more pronounced at the higher strain rate, 10^{-3} s^{-1}, where internal flaws

Table 2. Strength, structure, and porosity of selected ridge ice samples tested at -5°C (23°F).

Sample Number	Strength (MPa)	Strength (lbf/in.^{2})	Ice type	Grain size (mm)	Porosity (o/oo)
		Tested at a strain rate of 10^{-5} s^{-1}			
High strength					
R1B-320/346	7.52	1090	IIA-Aligned 0° Elongation	55x10	25.3
R5B-075/101	5.34	774	II A-Aligned 5° Elongation	17x6	72.3
R1B-429/445	4.80	696	IIA 5° Elongation	15x10	23.7
R8A-432/458	4.53	657	IIA-Aligned 5° Elongation	30x5	24.5
R5A-165/191	4.27	619	IIA 0° Elongation	15x3	16.9
R7A-342/368	4.19	607	IIC 0° Elongation	2-20	24.4
Intermediate strength					
R3B-363/387	2.72	394	IIIB	<1	15.3
R2A-140/165	2.68	388	I	2	10.1
R5B-341/367	2.54	368	I	<1	56.1
R7A-059/082	2.49	361	I	<1	69.5
R8B-515/541	2.40	348	IIB	20x5	23.8
Low strength					
R7B-241/267	1.58	229	III	5	77.8
R1A-226/252	1.48	214	IIA 40° Elongation	25x15	19.4
R1A-399/425	1.48	214	III	--	38.9
R2B-094/121	1.18	171	IIIB	<1	143
R7A-263/286	0.47	68	III 40° Elongation	35	154
		Tested at a strain rate of 10^{-3} s^{-1}			
High strength					
R1A-300/326	10.90	1580	IIA-Aligned 0° Elongation	55x10	20.3
R7B-440/466	10.62	1540	IIA-Aligned 5° Elongation	45x10	32.0
R8B-483/509	9.93	1440	IIA-Aligned 15° Elongation	50x15	25.6
R8B-384/410	8.94	1297	IIA 0° Elongation	40x10	24.2
R2A-285/310	8.76	1270	IIA 10° Elongation	25x15	22.3
R1B-175/201	8.76	1270	IIA 80° Elongation	--	16.2
R5B-141/167	8.76	1270	IIA 0° Elongation	45x25	21.1
Intermediate strength					
R3B-331/357	6.70	971	IIIB	<1	31.4
R3A-188/213	6.69	970	III	5	23.5
R3A-401/427	6.38	925	III	<1	21.0
R1B-216/241	6.31	915	IIA 40° Elongation	35x20	16.3
R4B-299/325	6.28	910	III	2-10	56.2
R4B-420/466	6.28	910	IIIA	35x10	53.0
Low strength					
R8B-300/326	4.05	587	III	--	15.1
R7B-175/201	3.84	557	IIC 50° Elongation	5	23.3
R7B-072/098	3.36	487	III	--	53.4
R2A-110/135	2.81	408	I	<1	86.9
R8A-033/059	2.39	346	IIIA	--	75.2



a. Strain rate of 10^{-5} s^{-1}.



b. Strain rate of 10^{-3} s^{-1}.

Figure 2. Uniaxial constant-strain-rate compression strength of ridge ice samples versus porosity for tests conducted at -5°C (23°F). The closed circles (•) represent columnar ice samples loaded parallel to the elongated crystal axis and perpendicular to the c-axis; the open circles (o) represent all other test samples.

and cavities play a more important role in brittle ice failure.

The observation that the strength of columnar sea ice varies with load orientation agrees with the findings of Peyton (1) and Wang (2) for first-year sea ice.

CONCLUSIONS

The maximum strength value that a multi-year ridge sea ice sample will attain depends on the sample structure and porosity. A columnar sample is predominantly influenced by the orientation of the elongated grains and hence the crystal c-axis orientation relative to the loading direction. Samples composed of granular ice or a mixture of granular and columnar have a strength largely dependent on porosity.

Obviously, much more work must be done to provide a more exact relationship between strength, structure and porosity. Reliable constitutive relationships approximating multi-year ridge behavior cannot be established until the interaction of the highly variable structure within the ridge is understood. This will require an estimation of the relative amounts of ice types within a ridge and the dominant failure mechanisms.

ACKNOWLEDGEMENTS

This study was sponsored by Shell Development Company and the Minerals Management Service of the U.S. Department of the Interior, with support from Amoco Production Company, Arco Oil and Gas Company, Chevron Oil Field Research Company, Exxon Production Research Company, Gulf Research and Development Company, Mitsui Engineering and Shipbuilding Company, the National Science Foundation, Sohio Petroleum Company, Texaco, the U.S. Department of Energy, and the U.S. Coast Guard.

REFERENCES

1. Peyton, H.R. "Sea ice strength." Geophysical Institute, University of Alaska, Report UAG-182, 1966.
2. Wang, Y.S. "Sea ice properties." Technical Seminar on Alaskan Beaufort Sea Gravel Island Design, Exxon Company, U.S.A., Houston, Texas, 18 October 1979.
3. Schwarz, J. and W.F. Weeks. "Engineering properties of ice." Journal of Glaciology, vol. 19, no. 8, 1977, pp. 499-530.
4. Cox, G.F.N., J.A. Richter, W.F. Weeks and M. Mellor. "The mechanical properties of multi-year sea ice, Phase I: Test results." U.S. Army Cold Regions Research and Engineering Laboratory, 1983.
5. Cox, G.F.N., J.A. Richter, W.F. Weeks, and M. Mellor. "A summary of the strength and modulus of ice samples from multi-year pressure ridges." Paper to be presented at the Third International Offshore Mechanics and Arctic Engineering Symposium, New Orleans, 1984.
6. Weeks, W.F. and A.J. Gow. "Preferred crystal orientations in the fast ice along the margins of the Arctic Ocean." Journal of Geophysical Research, vol. 83, no. C10, 1978, pp. 5105-5121.
7. Michel, B. "Ice Mechanics." Les Presses de l'Université Laval, Quebec, Canada, 1978.
8. Cherepanov, N.V. "Classification of ice of natural water bodies." Proceedings of the IEEE International Conference on Engineering in the Ocean Environment, Ocean 74, Halifax, Nova Scotia, vol. 1, 21-23 August 1974, pp. 97-101.
9. Cox, G.F.N. and W.F. Weeks. "Equations for determining the gas and brine volumes in sea ice samples." U.S. Army Regions Research and Engineering Laboratory Report 82-30, 1982, 11 pp.